Mars Rovers Land Right on the DIMES

- **Autonomous Vision-Guided Safe and Precise Landing software will enable planetary rovers to land safely in hazardous terrain**

- **Core components of the software helped Mars rovers safely reach their 300-million-mile destinations**

NASA's Mars Exploration Rover (MER) mission has sent two robot rovers, Spirit and Opportunity, to search for evidence that water once existed on the Red Planet. Both of the rovers' dramatic landings were assisted by the Descent Image Motion Estimation Subsystem (DIMES), which was built using core components of the Autonomous Vision-Guided Safe and Precise Landing (AVGSPL) software being developed under CICT's Intelligent Systems (IS) Project.

Autonomously adjusting to Martian winds, DIMES consists of a lightweight camera and core components of the AVGSPL software that calculate the rover spacecraft's horizontal motion during its final seconds of flight. The camera takes three successive photos of the Martian surface in the 18 seconds before each rover's braking rocket is ignited, and uses the photos to calculate any wind-generated horizontal movement away from its designated course.

Steve Squyres, the MER mission's principal investigator, said that on Spirit's landing DIMES "worked perfectly to figure out if wind was moving us and, when it determined that was the case, signaled to fire the mini retro rockets that straightened us up for landing." On Opportunity's landing, DIMES determined that sideways motion was minimal, so the system did not have to fire the lateral rockets.

A first step toward autonomous landings
Bob Morris, manager of the IS Project's Automated Reasoning (AR) subproject, says, "DIMES uses core components of more complex software being funded by the IS Project and developed by Jim Montgomery, Andrew Johnson, and their colleagues at NASA's Jet Propulsion Laboratory. They are developing machine-vision algorithms so that landers can identify safe landing sites and navigate locally using visual landmarks."

Adapting quickly to changing conditions
"The autonomous vision-guided landing algorithms," says Morris, "are part of our Intelligent Sensing and Reflexive Behavior Task, which addresses the pre-programmed actions and reflexes that form the basic vocabulary for higher-level reasoning in autonomous systems. These adaptive control and reflexive response capabilities enable a device to quickly adapt and respond to changes both within its environment and within itself."

The Mars Rovers' Descent Image Motion Estimation Subsystem (DIMES) uses a camera (upper left) and core components of CICT-funded vision-guided landing software to calculate and determine thruster compensation for the impact of Martian winds on the lander's course. The DIMES photo of Mars craters (left) was the Spirit rover's last before landing.

Technology Spotlight

Technology
Autonomous Vision-Guided Safe and Precise Landing (AVGSPL) software and core components of the MER Descent Image Motion Estimation Subsystem (DIMES)

Function
Enables spacecraft to autonomously land safely and precisely on hazardous terrain, even in windy conditions

Relevant Missions
- Mars Exploration Rover (MER)
- Mars Science Laboratory (and other Mars landers)
- Comet Surface Sample Return
- Lunar Surface Sample Return
- Europa Lander
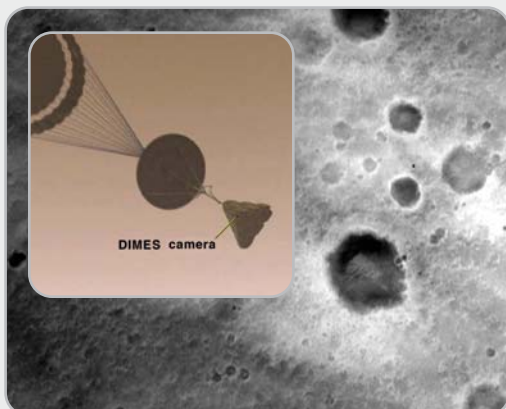- Titan Organics Explorer

Features
- Algorithm for building 3D model of the surface from video stream
- Algorithm for detecting landing site
- Algorithm for tracking moving position relative to the landing site
- Algorithms for controlling heading and attitude of the spacecraft
- Algorithm for landing the craft

Benefits
- Differentiates between hazardous (steep, rough) and safe (flat, smooth) areas of terrain
- Enables craft to compensate for horizontal winds
- Enables spacecraft to control descent for soft landing

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The complete AVGSPL software package is targeted at infusion into the Mars Science Laboratory mission (artist's rendition, left) slated for 2009. The software would provide the lander with accurate landing and hazard avoidance capabilities so that it can land itself at promising but difficult-to-reach scientific sites. In the illustration, the hazardous zones are seen as red, and the safe landing spot as a green cross in the yellow area.

Jim Montgomery, principal investigator for the AVGSPL software research, says, "An unmanned Mars lander may spend less than two minutes in its entire descent phase, which allows very little time for reasoning about navigation, sensors, and landing hazards. Our goal is to give these craft the ability to evaluate the landing area quickly and to respond quickly. Andrew Johnson is developing the algorithms that make this possible, and he also developed the DIMES subset that assisted the Mars rovers."

"Our research," says Andrew Johnson, "focuses on developing vision-based systems that enable safe and precise landing with little addition to spacecraft mass, power, and volume. Our algorithms use monocular image streams to provide estimates of motion and position relative to the target, rapidly construct 3D surface topography models to assess hazards and select a safe landing site, and then control descent for a precise landing."

A breakthrough in autonomous landing
Over the past few years, several groups have pursued vision-based control of aerial robots, but earlier real-time computer vision systems designed to track a landing target were not accompanied by actual landings, and earlier publications of vision-based techniques for autonomous control did not focus on the landing problem. The research done by Montgomery and Johnson is distinguished by their successful integration of the different capabilities most likely needed by a spacecraft to autonomously land on unknown terrain. They have demonstrated Johnson's algorithms successfully in simulation, on a three-degrees-of-freedom (3DOF) gantry testbed, and on an autonomous two-meter-long model helicopter. As far as they know, they are the first to demonstrate a system that enables a craft to autonomously determine a safe, flat spot to land in otherwise uneven terrain without predetermined landmarks.

Achieving autonomous flight
"We are using the helicopter as a real-time, hardware-in-the-loop testbed for developing and validating vision algorithms," says Montgomery. "The helicopter will not be used for future space missions, but hopefully our algorithms will.

"For the helicopter to fly autonomously," says Montgomery, "we used an architecture that partitions flight control into a hierarchy of loosely coupled behaviors responsible for different tasks. Low-level reflexive control behaviors maintain heading, attitude, and altitude by generating actuator commands that reduce the error between desired and measured values. This ensures stable hover and low-speed flight. The desired values come from higher-level behaviors such as navigation control. The measured values for heading and attitude come from a Kalman filter that combines data from onboard sensors. The measured altitude comes from a geographical positioning system (GPS) and a laser altimeter.

"A mid-level lateral control behavior provides the attitude control behavior with roll and pitch angles for achieving a desired lateral velocity. The high-level navigation control behavior provides lower-level behaviors with the heading, altitude, and lateral velocity for navigating to a desired 3-D position in space."

How the system lands the craft
"To land," says Johnson, "the craft takes a stream of digital pictures and height measurements of the landscape using an onboard camera and laser altimeter. From these measurements, the vision algorithms construct an elevation map, using a technique called 'dense structure from motion.' Software operators are then applied to the terrain map to find a landing site that is free of steep slopes and rocky terrain.

"Once the safe site is identified," says Johnson, "the craft enters object-track mode, in which the state estimation algorithm sends commands to the autonomous flight controller. When the craft is above the targeted landing spot, the vision-based controller commands the craft to enter landing mode."

"Autonomous flight control is difficult due to its non-linear, cross-coupled dynamics," says Montgomery. "It's a challenge to smoothly integrate the operation of the pitch, roll, and yaw controls to precisely maneuver the craft. Even more difficult is autonomous landing due to the disturbances from ground effect injected into the system when hovering right before landing."

Using their AVGSPL system, Montgomery and Johnson demonstrated that the model helicopter could successfully land repeatedly and accurately within one meter of target center. Since that successful demonstration, the algorithms used in DIMES have proven equally effective in ensuring that the rovers Spirit and Opportunity reached their targets. These were important first steps in enabling the future Mars Science Laboratory to succeed as well.

–Larry Laufenberg

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